Inverters in Microgrids

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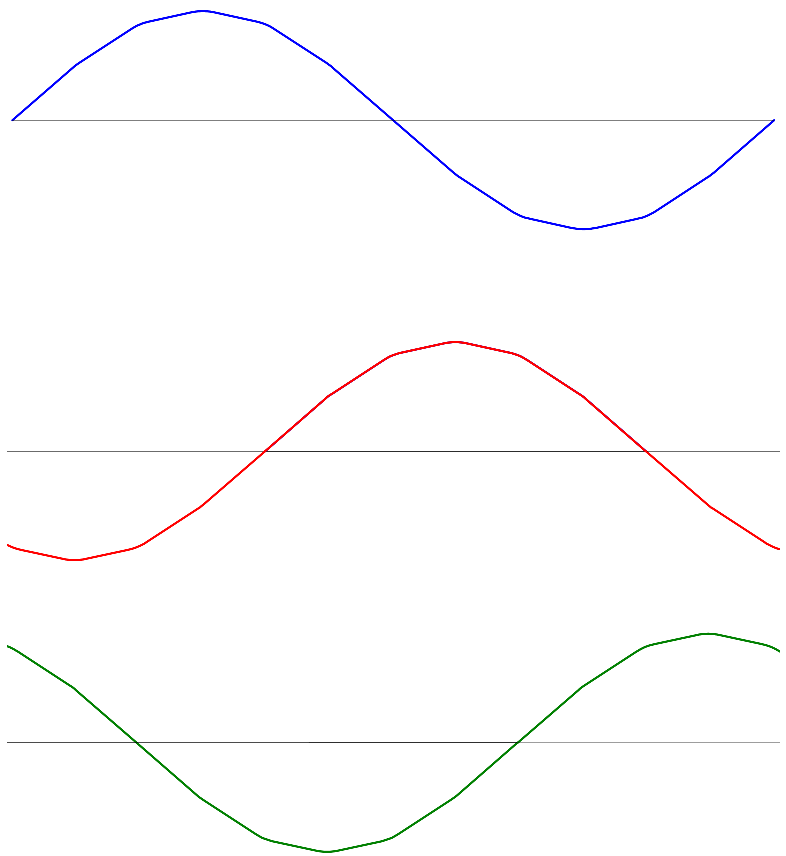
Outline

- Electric grid operations
- Frequency and voltage control
- Inverter based generation
- Inverter dynamic modeling
- Summary

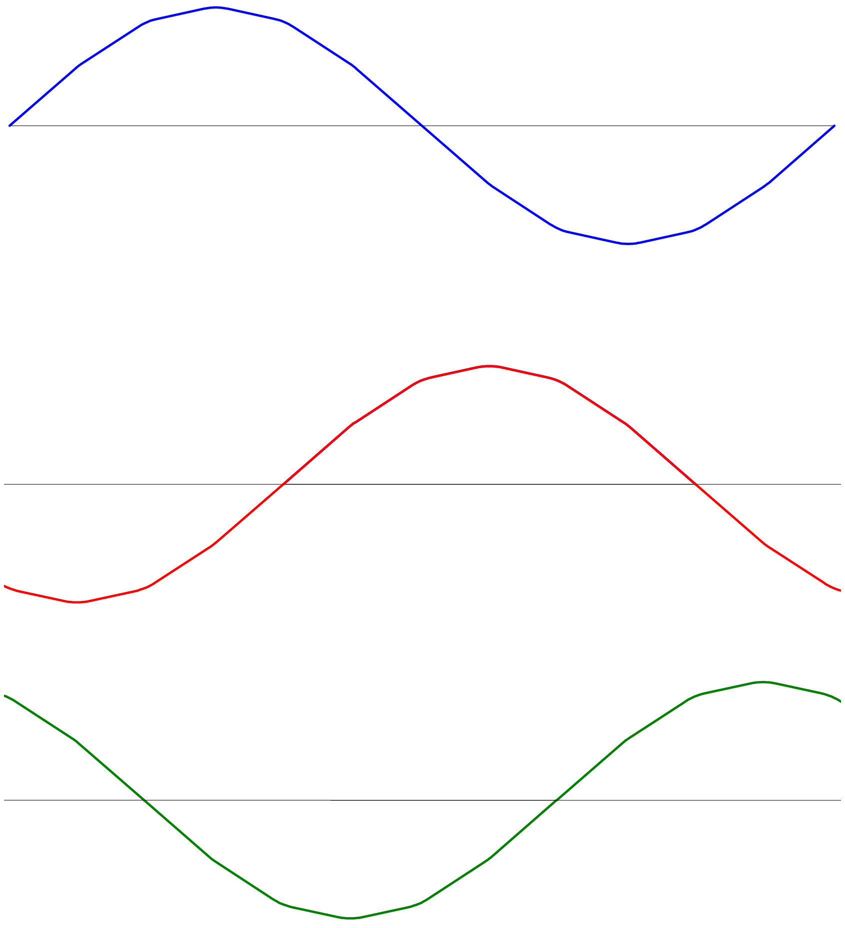
Electrical generation

- Rotating machines
- Primarily synchronous machines
- Three phase ac output



Alternators

- Frequency
  - Tied to the speed of the shaft
- Voltage
  - Tied to the field excitation



Frequency Regulation (lone machine)

- Shaft speed

  mechanical shaft power equal to electrical load power + losses

- Speed governors

  Measure shaft speed

  Adjust energy (fuel) input to increase or decrease speed

Frequency Regulation (Grid)

- Cannot have several machines trying to control speed set point locally with zero error – lead to chaos
- Allow all but one machine to have set-point errors
- All machines work on a dispatched power set point, speed follows the master
- Master machine follows the load power demand and regulates the frequency

Voltage Regulation (lone machine)

- Field regulator
  - Measure terminal voltage
  - Adjust field excitation input to increase or decrease voltage
- Field excitation
  - Reactive power output equal to reactive power demand of load

Voltage Regulation (Grid)

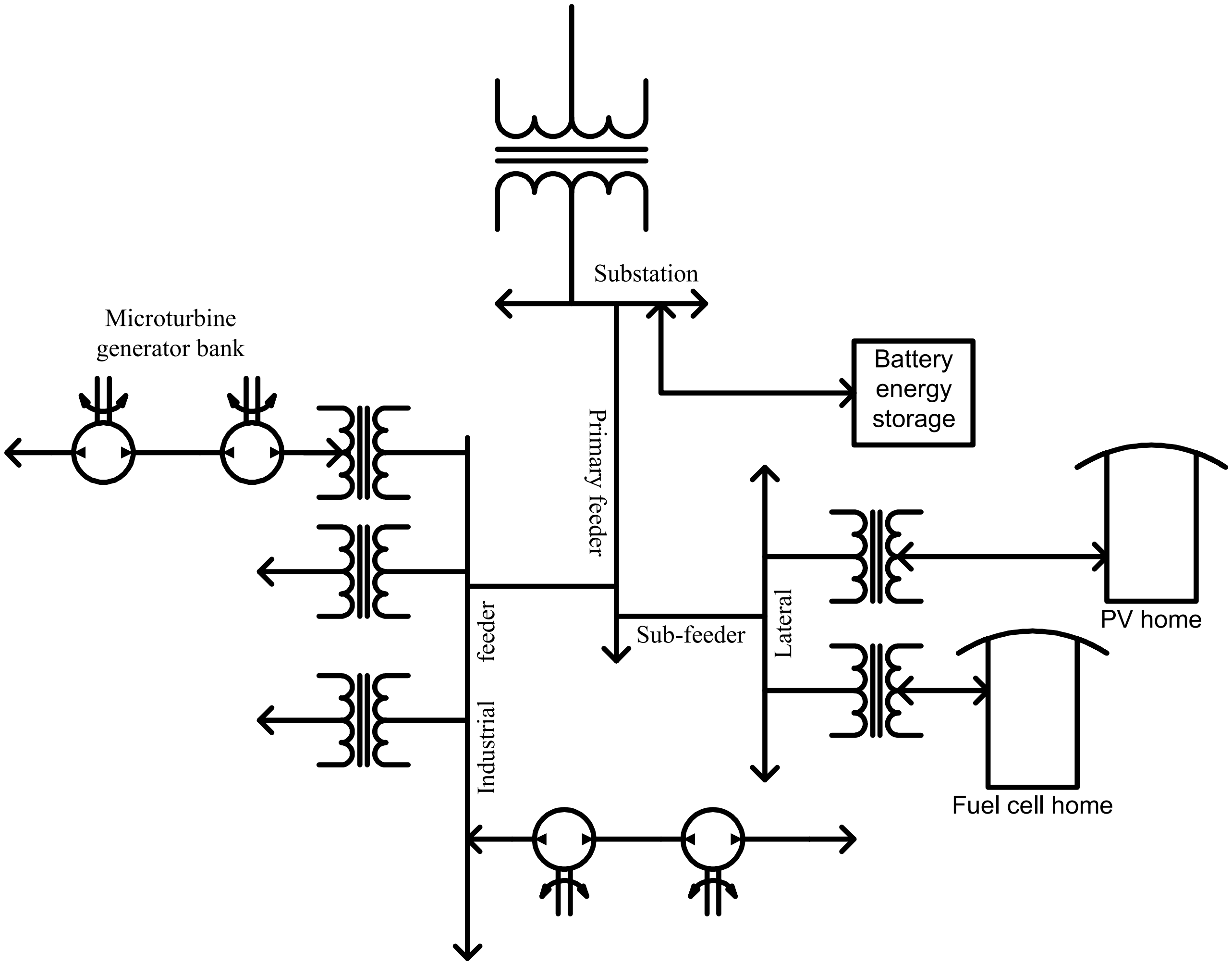
- Need appropriate voltage set points
- Improper set-points will lead to circulating currents between machines
- Typically local reactive power control loops

Distributed Generation

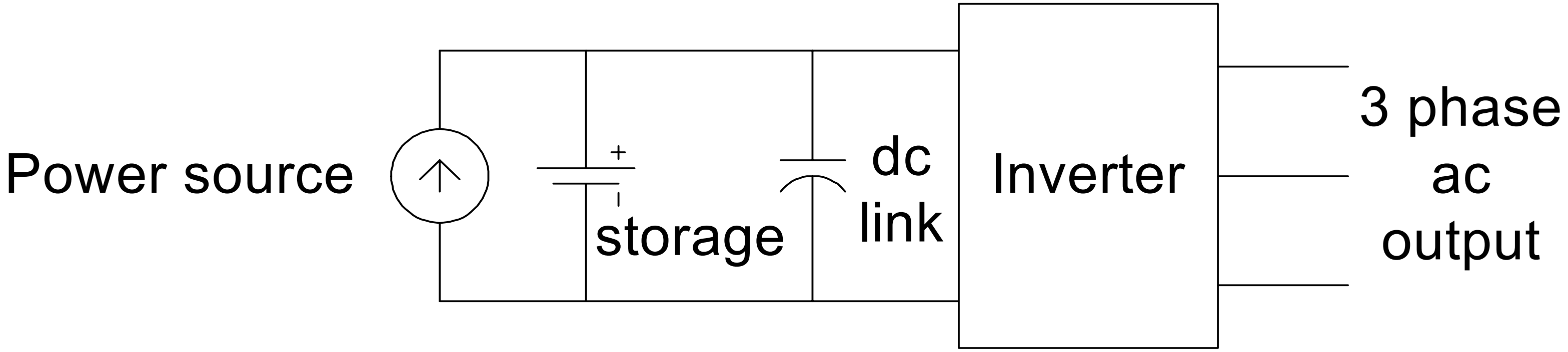
- Conventional reciprocating engines
- Wind generators
- Photovoltaics
- Microturbines
- Fuel cells
- Wave energy

- Significant fraction of generation in the future

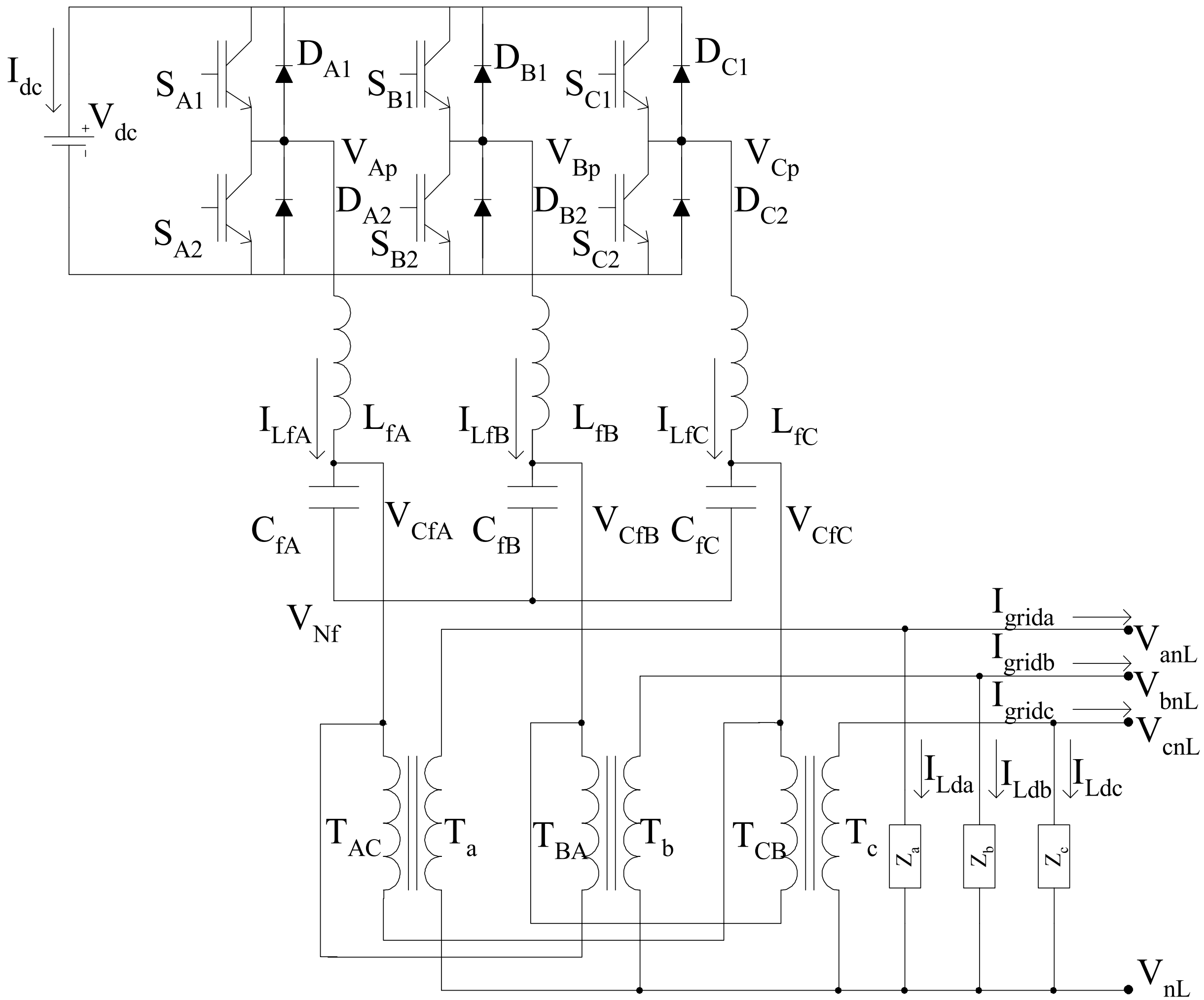
Distributed Generation



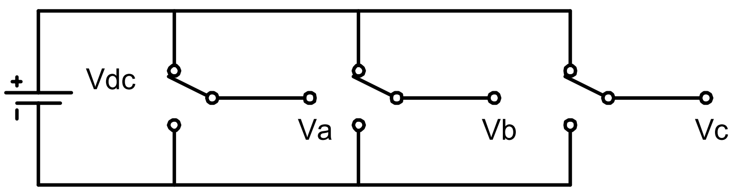
Inverter embedded generation

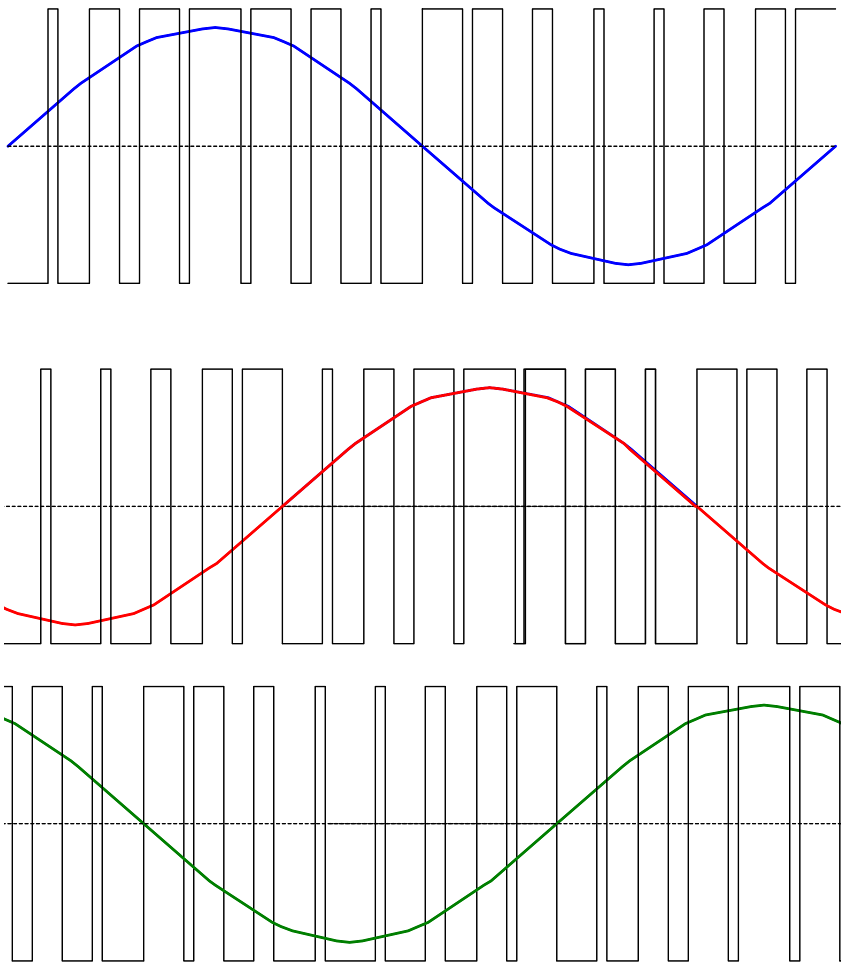


Inverter details



PWM Synthesis – A, B & C phases





- Phase shift between waveforms may be varied
- Amplitude of waveforms may be dissimilar
- All the three phase voltages could have an average Vdc/2 common mode voltage
- Causes a neutral shift
- Will cancel out in the line-line voltages

Microgrid Energy and Power Quality Management Functions

- Load profile control
- Source utilization
- Peak-shaving
- Reactive power injection

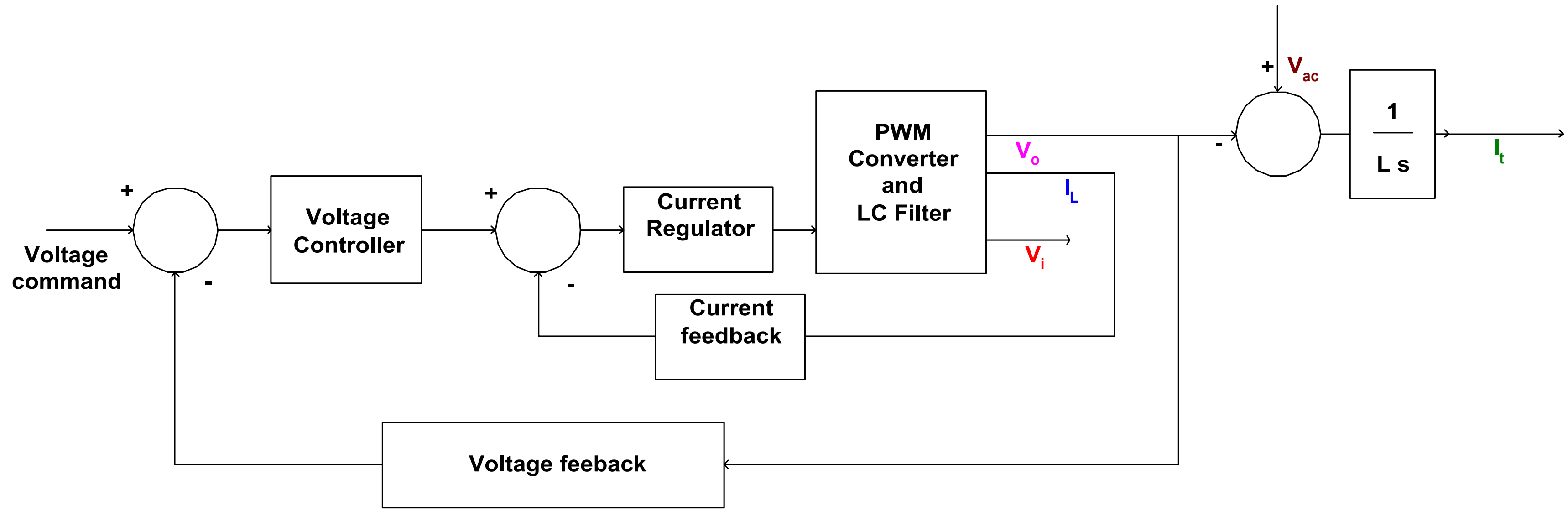
- POL voltage control
- Voltage imbalance correction

Key Control Issues

- Power flow control
- Frequency control
- Local voltage control
- Reactive power control

- Power sharing
- Frequency matching

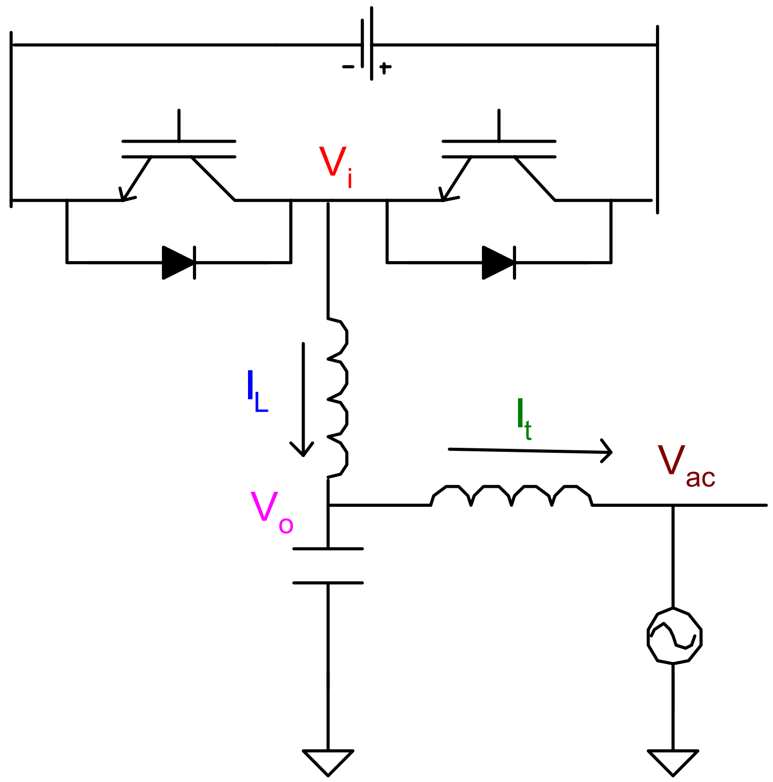
Typical controller structure (classical)

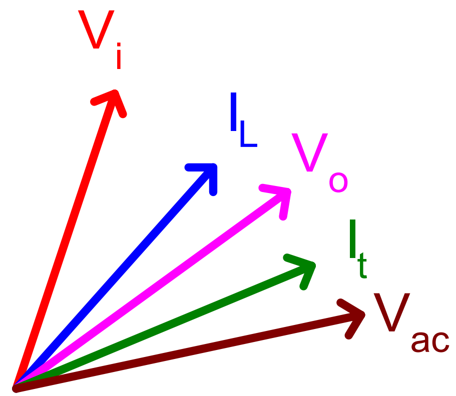


Typical Control Trend Today

- Operate as a balanced current source under utility connected operation
- Operate as a balanced voltage source under stand-alone operation
- Interchange from one mode to another requires anywhere between 10 seconds and 30 minutes

Single line equivalent circuit and phasor diagram





- Vac – PCC voltage
- Vo – Point of Connection (POC) Voltage

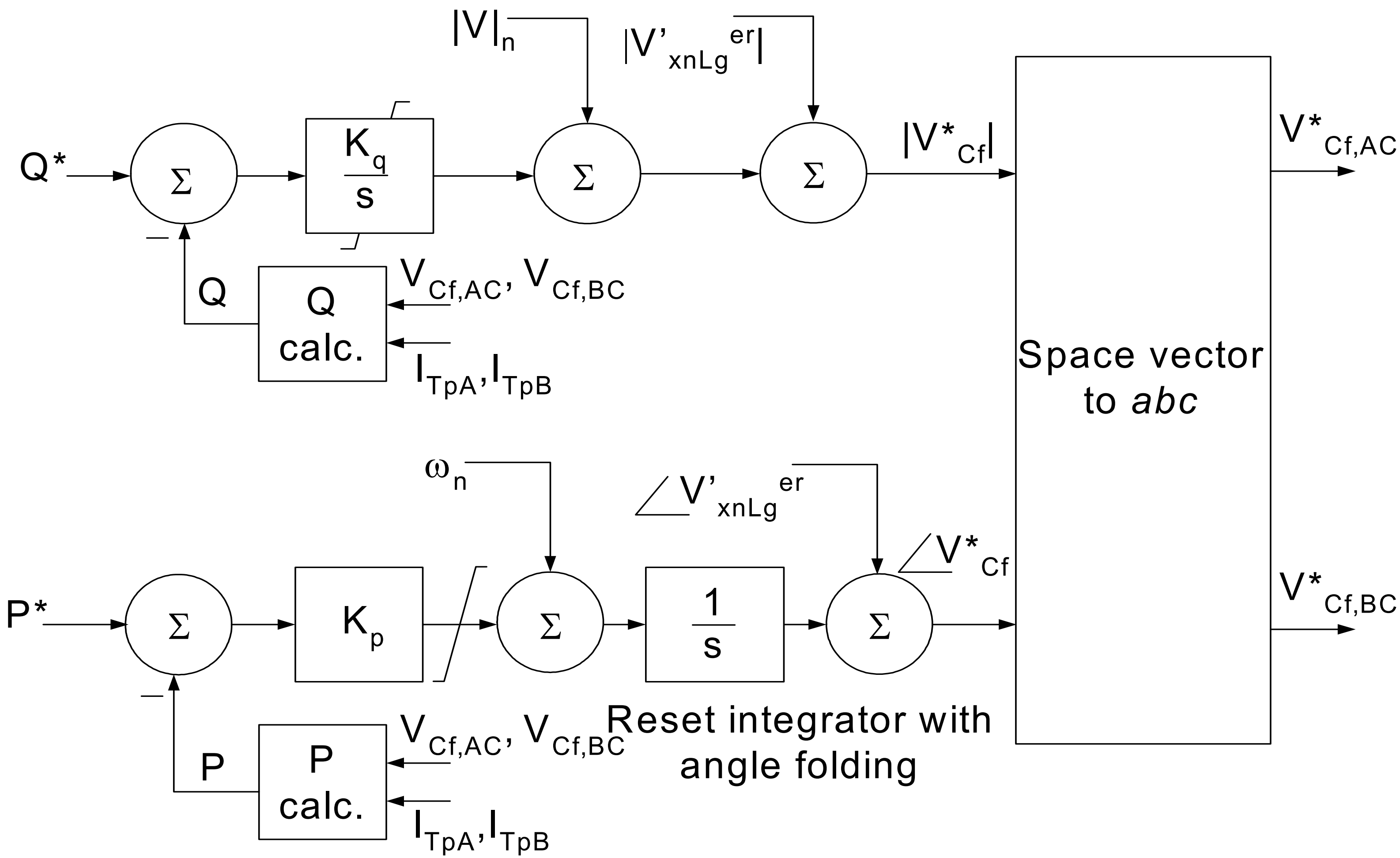
Power throughput of inverter

$$P = \frac{V_{ac} V_o}{X_t} \sin \delta$$

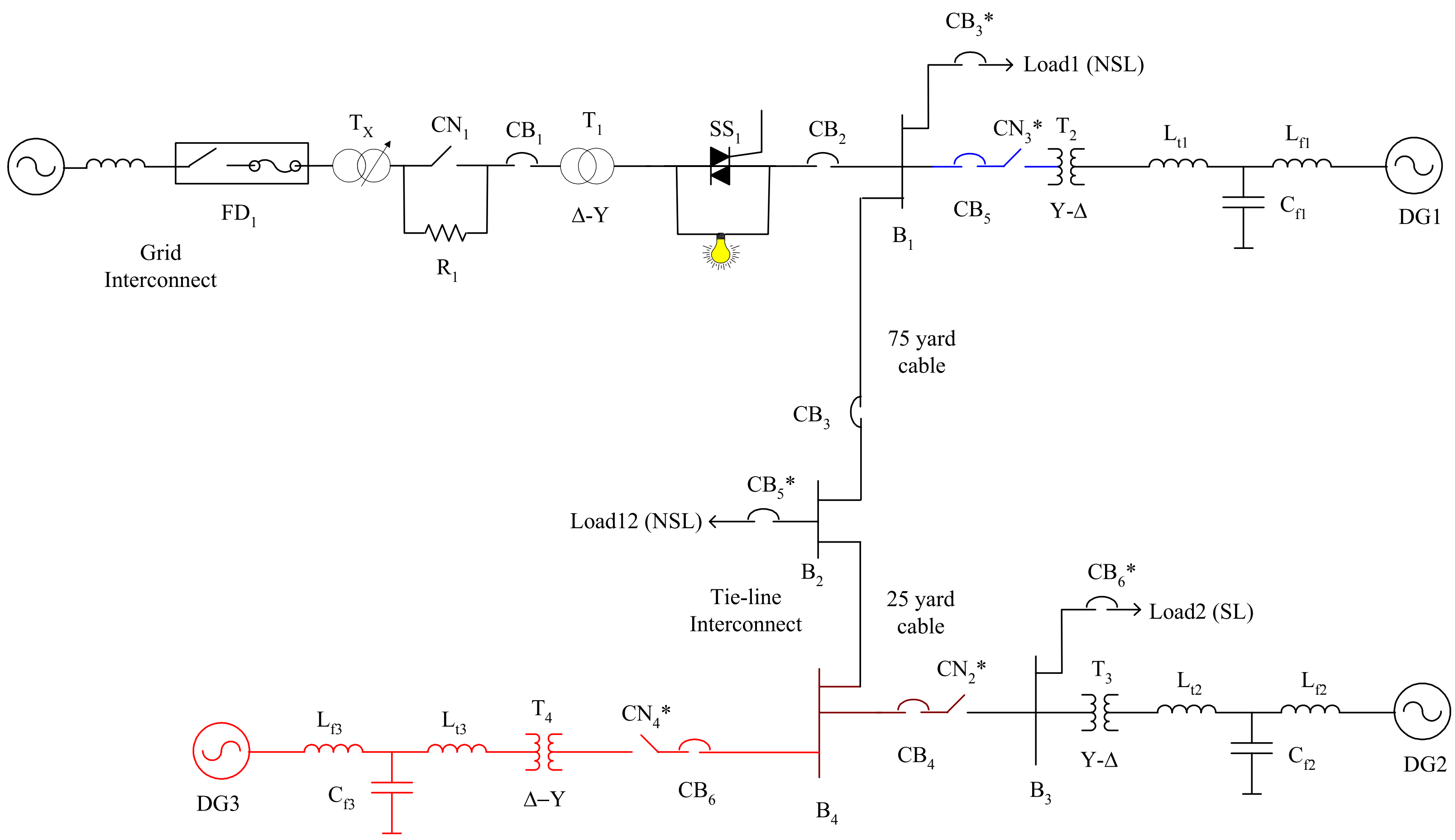
$$Q = \frac{V_o^{\,2}}{X_t} - \frac{V_{ac} V_o}{X_t} \cos \delta$$

- Angle between V_{ac} and V_o determines power flow
- Magnitude of V_o determines reactive power flow

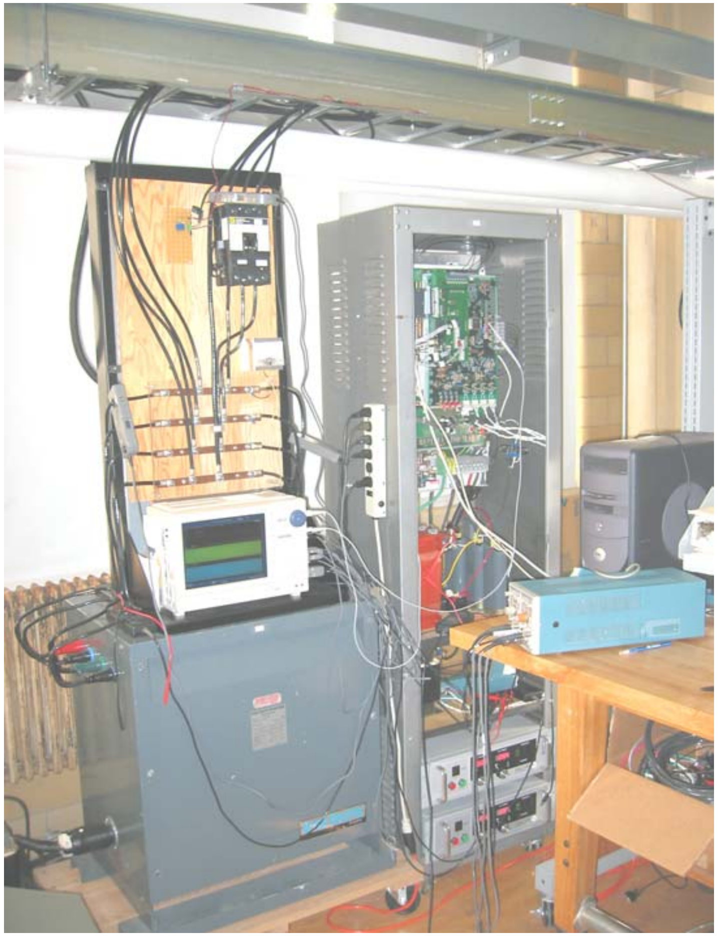
Inverter controls

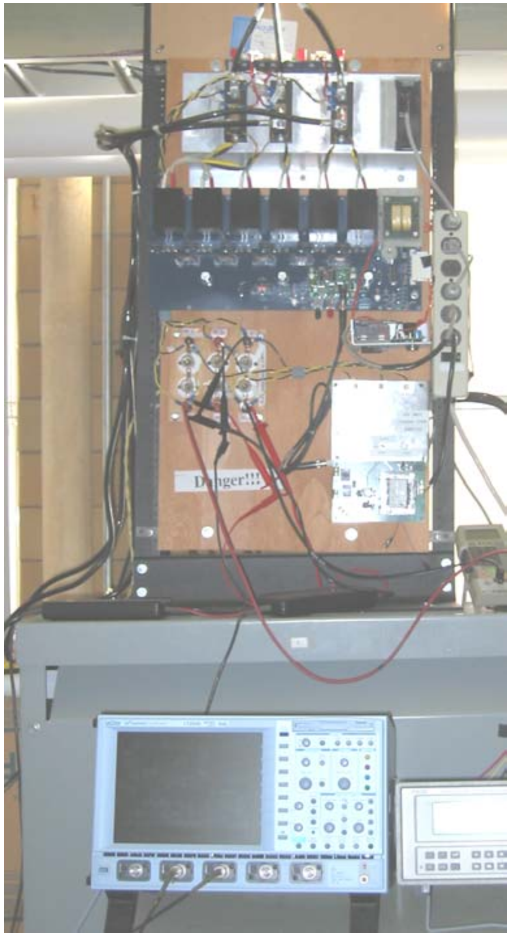


Laboratory scale microgrid



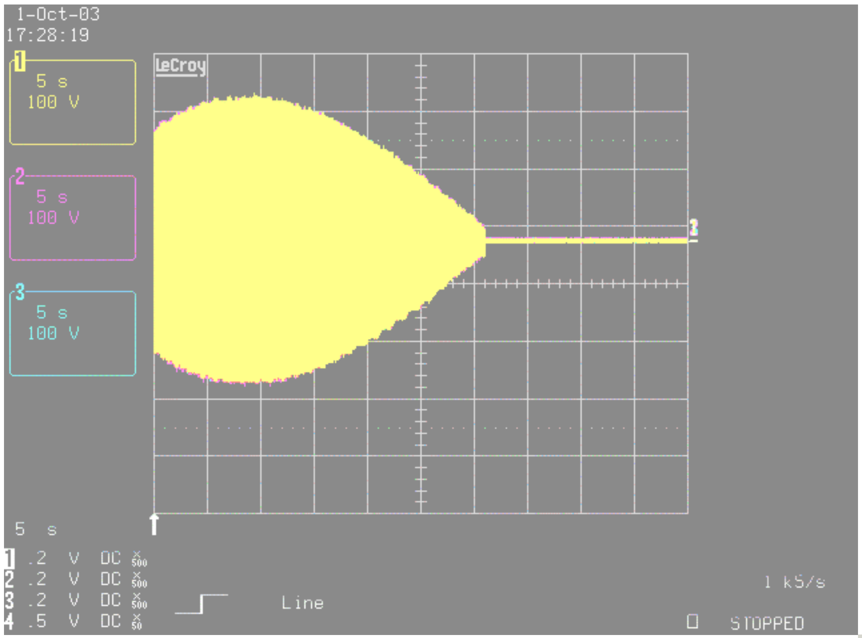
Laboratory scale microgrid hardware details





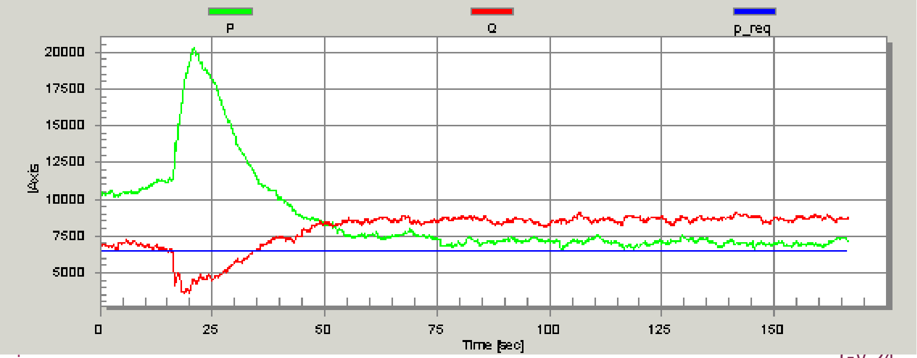
Laboratory scale microgrid hardware details

Laboratory scale microgrid hardware results



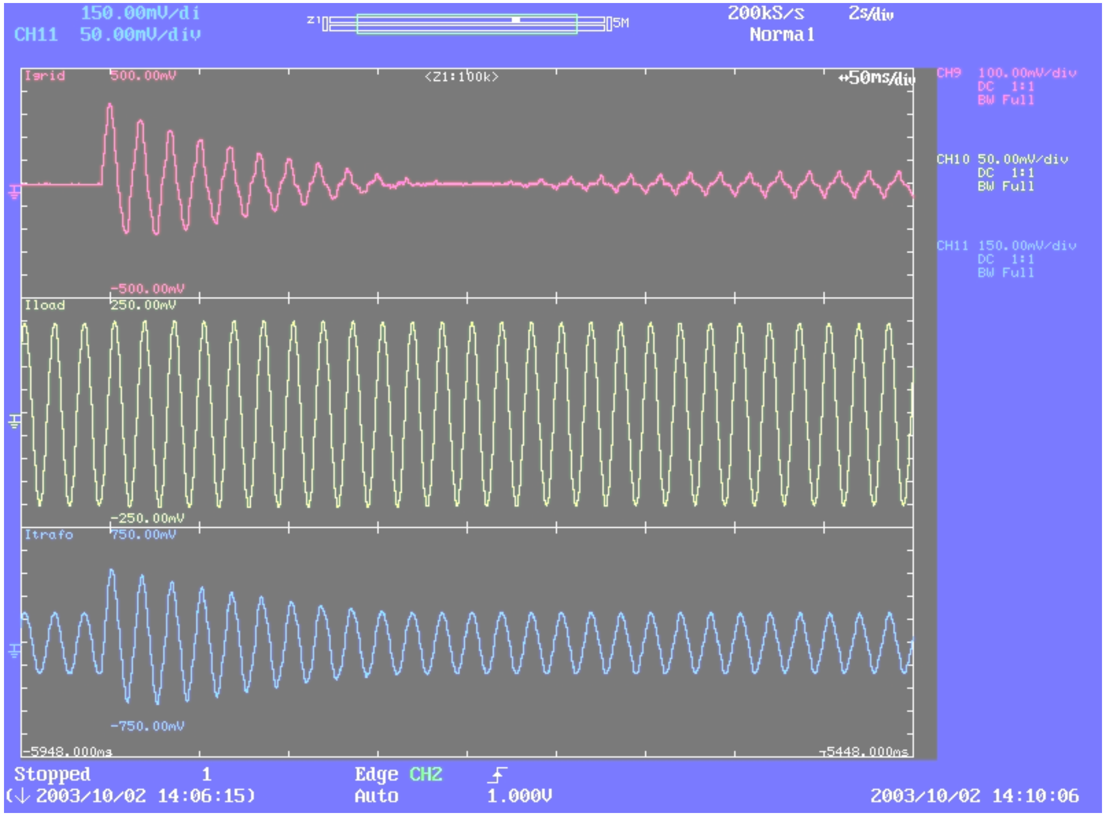
Synchronization to grid 'beat voltage'

P and Q transients



WEMPEC

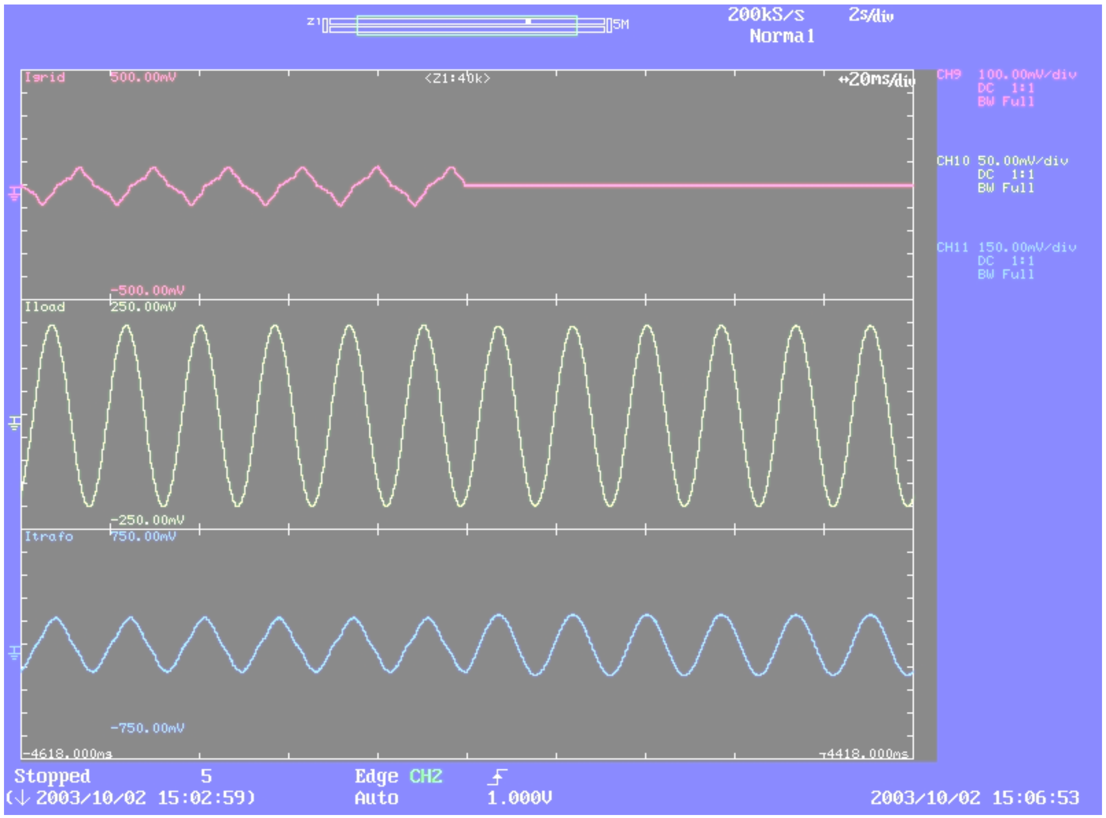
Laboratory scale microgrid hardware results



Synchronization to grid

Voltage and current waveforms

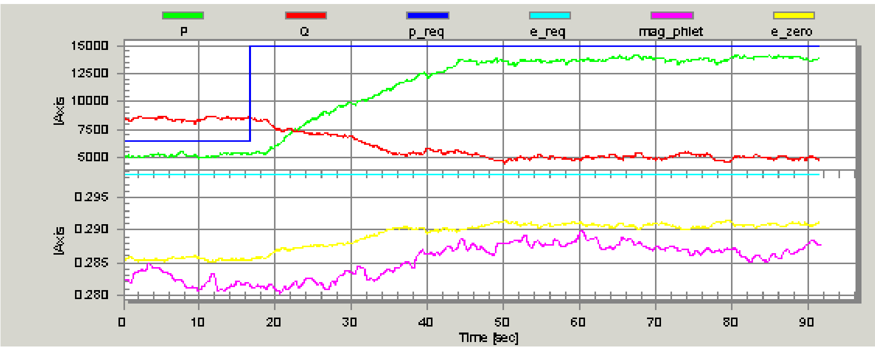
Laboratory scale microgrid hardware results



Disconnection from grid

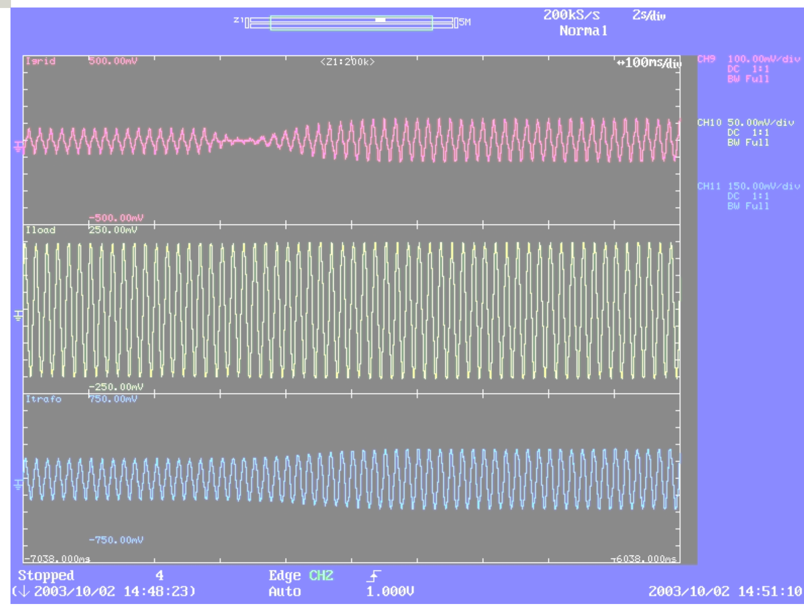
Voltage and current waveforms

Laboratory scale microgrid hardware results

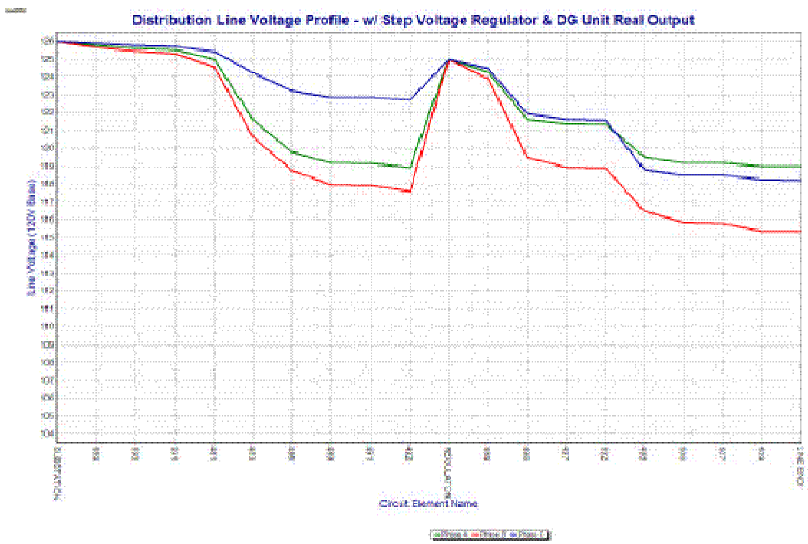


Step response of power

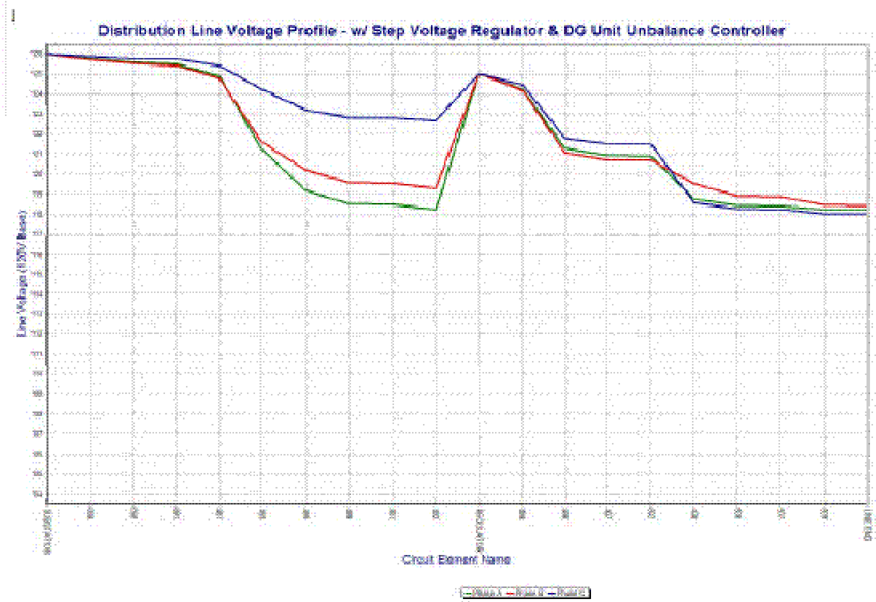
Voltage and current waveforms



Computer simulations



Voltage profile along an unbalanced distribution feeder
with conventional dg control



Voltage profile along an unbalanced distribution feeder
with unbalanced dg control

Modeling objectives

- Need to model dynamic properties
- Control input and real power flow or power angle
- Control input and reactive power flow or voltage magnitude

Key control variables

$$m(t) = |m(t)| e^{j\angle m(t)}$$

$$v_i(t) = |v_i(t)| e^{j\angle v_i(t)}$$

$$i_L(t) = |i_L(t)| e^{j\angle i_L(t)}$$

$$v_o(t) = |v_o(t)| e^{j\angle v_o(t)}$$

Instantaneous phase quantities are projections of the rotating vectors on appropriate axes

Dynamic Equations

$$L\frac{d}{dt}i_L = v_{dc}|m|\cos(\angle m - \angle i_L) - |v_o|\cos(\angle v_o - \angle i_L)$$

$$L|i_L|\frac{d}{dt}\angle i_L = v_{dc}|m|\sin(\angle m - \angle i_L) - |v_o|\sin(\angle v_o - \angle i_L)$$

$$C\frac{d}{dt}|v_o| = |i_L|\cos(\angle i_L - \angle v_o) - \frac{|v_o|}{R}$$

$$C|v_o|\frac{d}{dt}\angle v_o = |i_L|\sin(\angle i_L - \angle v_o) - \frac{|v_o|}{R}$$

Steady state operating condition

$$0 = V_{dc}\left|M\right|\cos(\angle M - \angle I_L) - \left|V_o\right|\cos(\angle V_o - \angle I_o)$$

$$L\left|I_L\right|\omega = V_{dc}\left|M\right|\sin(\angle M - \angle I_L) - \left|V_o\right|\sin(\angle V_o - \angle I_L)$$

$$0 = \left|I_L\right|\cos(\angle I_L - \angle V_o) - \frac{\left|V_o\right|}{R}$$

$$C\left|V_o\right|\omega = \left|I_L\right|\sin(\angle I_L - \angle V_o) - \frac{\left|V_o\right|}{R}$$

Steady state operating condition

$$0 = V_{dc}\left|M\right|\cos(\phi_{mi_L}) - \left|V_o\right|\cos\phi_{v_o i_L}$$

$$L\left|I_L\right|\omega = V_{dc}\left|M\right|\sin\phi_{mi_L} - \left|V_o\right|\sin\phi_{v_o i_L}$$

$$0 = \left|I_L\right|\cos\phi_{i_L v_o} - \frac{\left|V_o\right|}{R}$$

$$C\left|V_o\right|\omega = \left|I_L\right|\sin\phi_{i_L v_o} - \frac{\left|V_o\right|}{R}$$

Classical phasor solution

Small signal model at operating point

$$\dot{x} = Ax + Bu$$

$$y = Ex + Fu$$

$$u = \left|\tilde{m}\right|$$

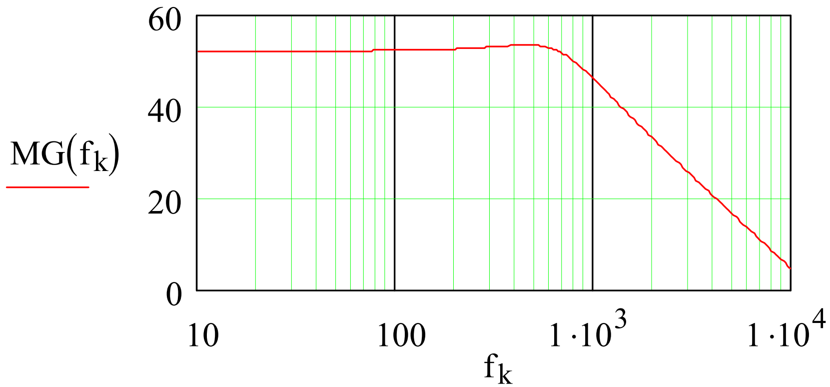
$$x = \begin{bmatrix} \left|\tilde{i}_L\right| \\ \angle\tilde{i}_L \\ \left|\tilde{v}_o\right| \\ \angle\tilde{v}_o \end{bmatrix}$$

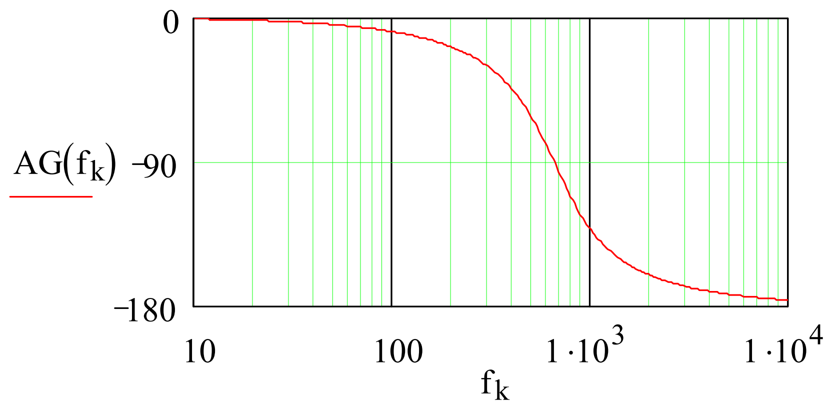
$$A = \begin{bmatrix} 0 & \omega I_L & \dfrac{-\left|V_o\right|}{LR\left|I_L\right|} & \dfrac{-\omega C\left|V_o\right|^2}{\left|I_L\right|^2 L} \\ \dfrac{-\omega}{\left|I_L\right|} & 0 & \dfrac{-\omega C\left|V_o\right|}{\left|I_L\right|^2 L} & \dfrac{-\left|V_o\right|^2}{LR\left|I_L\right|^2} \\ \dfrac{\left|V_o\right|}{RC\left|I_L\right|} & -\omega\left|V_o\right| & \dfrac{-1}{RC} & \omega\left|V_o\right| \\ \dfrac{\omega}{\left|I_L\right|} & \dfrac{1}{RC} & \dfrac{-\omega}{\left|V_o\right|} & \dfrac{-1}{RC} \end{bmatrix}$$

$$B = \begin{bmatrix} \dfrac{V_{dc}\cos\phi_{mi_L}}{L} \\ \dfrac{V_{dc}\sin\phi_{mi_L}}{L\left|I_L\right|} \\ 0 \\ 0 \end{bmatrix}$$

Transfer function

- Magnitude of modulation to output voltage





Dynamic interaction issues

- Angle input to output transfer functions
- Cross coupling transfer functions
- Selection of controllers and tuning
- Outer loop effects (Real and reactive power, droop, etc.)
- Frequency synchronization
- Interactions between multiple parallel units
- Measurement delays, uncertainties, imbalances, etc.